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SEARCH FOR FRACTIONALLY CHARGED PARTICLES IN COSMIC RAYS NEAR SEA LEVEL*

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An array of spark chambers and scintillation-counter trays has been used to search for fractionally charged particles in cosmic rays near sea level. No acceptable events have been found with energy losses by ionization between 0.04 and 0.7 that of singly charged minimum-ionizing particles. This experiment sets new upper limits for the fluxes of fractionally charged particles in cosmic rays, namely, 1.7×10^{-10} and 3.4×10^{-10} $cm^{-2}\ sr^{-1}\ sec^{-1}$ (90% confidence) for minimum-ionizing particles with charges $\frac{1}{3}$ and $\frac{2}{3}$, respectively.

Since Gell-Mann[1] and Zweig[2] proposed that all strongly interacting particles are composed of fractionally charged objects, several authors[3-9] have reported on their searches in cosmic rays for these particles (quarks) using scintillation-counter arrays. An experiment is now running at the California Institute of Technology using an array of spark chambers and plastic scintillation counters to look for particles in cosmic rays near sea level which have energy losses by ionization anywhere between 0.04 and 0.7 that of singly charged minimum-ionizing particles. The system has an acceptance of 0.15 m^2 sr and has been operated for 3300 h. During this time, 1.5×10^8 cosmic-ray particles have traversed the array and no acceptable events have been found.

The arrangement of the two four-gap spark chambers and the 12 plastic scintillation counters paired into six counter trays is illustrated in Fig. 1. The resolution of the counters is 25% full width at half-maximum in all but two counters for which it is 45%. A trigger was generated when pulses between 0.03 and 0.7 that for minimum-ionizing particles occurred in all counter trays. The spark chambers have 1-cm gaps filled with a mixture of 75% argon, 24% helium, and 1% ethanol at atmospheric pressure.

Since it was imperative in this experiment that the pulse heights recorded from the counters corresponded to the particle whose track was observed in the spark chambers, a system of two lights was used to indicate the passage of another particle within the sensitive time of the chambers. For each trigger, oscilloscope

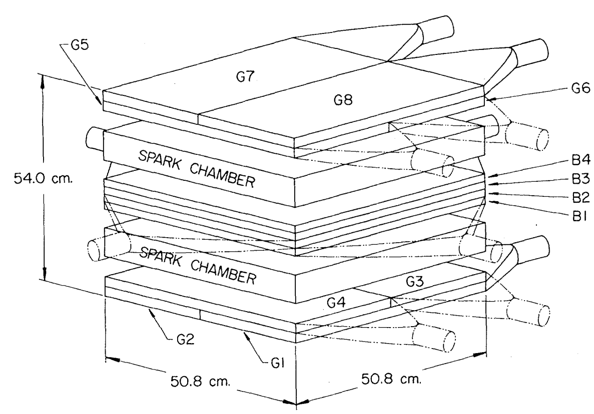

FIG. 1. The arrangement of the two spark chambers and the 12 plastic scintillators paired into six counter trays. G scintillators, 2.5 cm thick; B scintillators, 1.9 cm thick.

traces of the counter outputs, the spark chambers, and the light system were photographed, and the counter pulse heights were recorded by a multi-input 100-channel charge-sensitive pulse-height analyzer.[10]

At least twice a week, runs were taken with all of the counter outputs attenuated by a factor of 5 with passive networks in order to accept minimum-ionizing cosmic-ray particles. These runs were used to calibrate the overall gain of the system and to monitor the efficiency of the spark chambers for minimum-ionizing particles. Immediately after these runs, a pulser whose output pulse shapes matched those from the counters was used to calibrate the electronics and the oscilloscopes and to check discriminator levels.

The spark-chamber film was scanned for events with a single track in each chamber. It was required that the tracks were roughly aligned with at least two sparks in one chamber and three in the other and that there be no "extra particle" lights.[11] Out of the 59 300 pictures taken, 300 satisfied the above requirements.

A computer program was used to convert the pulse-height data to a normalized linear scale using the information from the periodic calibration and cosmic-ray runs. The successful events were then subjected to several additional tests. All corrected pulse heights were required to be between 0.04 and 0.7 minimum. A modified χ^2 for the six pulse heights, taking into account the skewed Symon-Landau distribution,[12-14] was calculated for each event, and was required to be less than 50. (This limit accepted more than 99 % of the single cosmic-ray events.[15]) Finally, consistency was required between the particle trajectory indicated by the spark chambers and that indicated by the particular combination of counters. One event survived the above analysis.

For this event, the angle between the two spark-chamber tracks and the distance between their intercepts with a plane located between the two spark chambers were measured in two stereoscopic views and compared with the distribution of these quantities as measured with cosmic-ray particles. This measurement showed

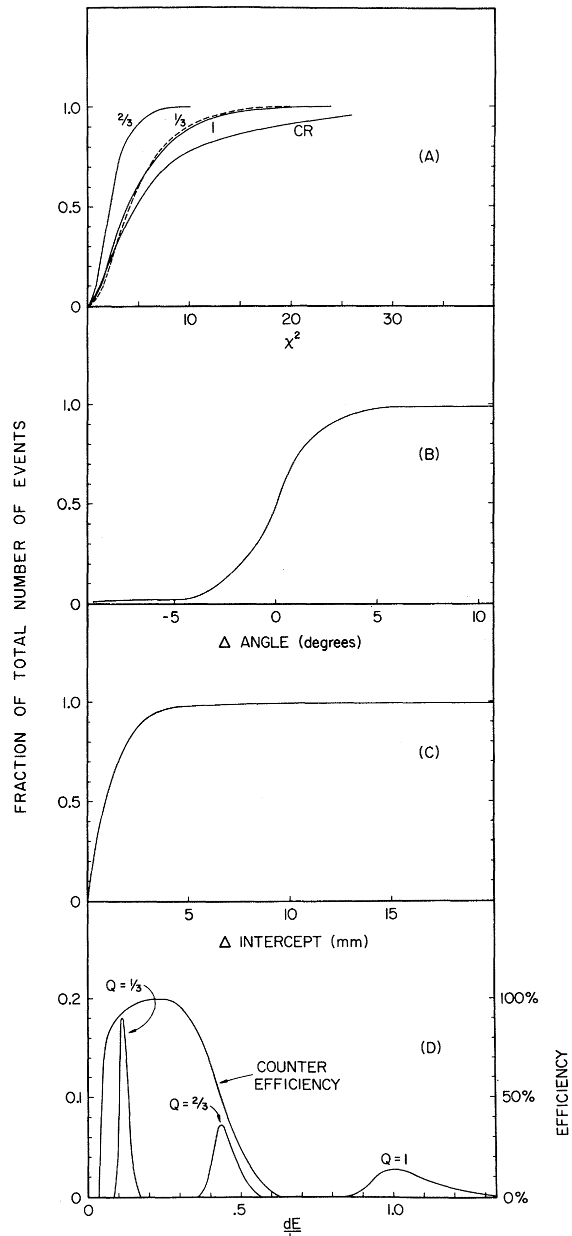

FIG. 2. (a) The integral distributions of the number of events as a function of χ^2 computed for Monte Carlo-generated events for charges 1/3, 2/3, and 1 and for cosmic-ray events (CR). (b) The integral distributions of the number of single-particle cosmic-ray events as a function of the angular misalignment of the tracks in the two spark chambers as seen in one projected view. (c) The integral distributions of the number of single-particle cosmic-ray events as a function of the absolute difference (lateral misalignment) between the intercepts of the tracks with a plane centered between the two spark chambers as seen in one view on a projection screen. (d) The detection efficiency of the counter array for pulse heights between 0.04 and 0.7 minimum as a function of the energy loss of a particle, and the differential distributions of the number of Monte Carlo-generated events per energy-loss interval computed for charges 1/3, 2/3, and 1 as a function of energy loss.

that the probability was 10^{-3} that the tracks could have been produced by a single particle traversing the system.

Detection efficiencies were computed by a Monte Carlo calculation using the cosmic-ray data and theoretical predictions on Symon-Landau fluctuations, photoelectron statistics, and the distribution of path lengths in the counters. The resulting χ^2 integral distributions are shown in Fig. 2(a); the most probable pulse-height distributions are shown in Fig. 2(d). The efficiency of the film scanning was determined to be 90 % by rescanning a portion of the film. The efficiency of the pulse-height analyzer for recording data was found to be 96 %. The criteria used to define the alignment of tracks rejected less than 2 % of single-particle cosmic-ray events. The integral distributions of the angular difference between the two tracks and the difference of the intercepts of both tracks with a plane centered between the two chambers are shown in Figs. 2(b) and 2(c), respectively.

The spark chambers were assumed to be 100% efficient for particles with energy losses between 0.1 and 0.7 minimum. That the efficiency is 100 % is not obvious since $\frac{1}{9}$ minimum produces on the average only eight electrons per gap for the gas mixture used, of which about half are effectively lost since they occur in infrequent delta rays. However, a preliminary test suggests that this efficiency is over 90 %. Further tests to determine the spark-chamber efficiency are in progress.

With this assumption, the upper limits for the fluxes of fractionally charged particles in cosmic rays near sea level as set by this experiment are lower than those established by previous experiments. In particular, we find the upper limits to be 1.7×10^{-10} and 3.4×10^{-10} $\mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{sec}^{-1}$ with 90% confidence for minimum-ionizing particles with charges $\frac{1}{3}$ and $\frac{2}{3}$, respectively.

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